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THESIS

OPTICAL PHASE CONJUGATION VIA
STIMULATED BRILLOUIN SCATTERING IN
CARBON DISULFIDE

by

Kenneth Patterson Morton

June 1985

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Optical Phase Conjugation via Stimulated Brillouin Scattering
in Carbon Disulfide

By

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Lieutenant, United States Navy
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ABSTRACT

The interaction of a strong, monochromatic beam of light with liquid CS_2 can produce a backscattered wave that is a phase conjugate replica of the input beam. A Nd-glass laser focused into an unguided cell returned 33% of the incident energy in the backscattered wave. Normal reflection from the glass surfaces of the lens and cell can account for only 2.5% of this energy. Observations were also made concerning the distortion repairing qualities of the phase conjugate wave and the sensitivity of the process to multimode excitation. Finally, appreciable visible fluorescence was observed when phase conjugation occurred.

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I. INTRODUCTION

Optical phase conjugation is a nonlinear optical phenomenon that is receiving considerable interest. This process offers an alternative to adaptive optics and occurs in a variety of materials by means of several different physical processes. For example, the following nonlinear phenomenon can produce optical phase conjugation:

- Brillouin scattering
- Raman scattering
- Kerr-like four-wave mixing
- Resonant four-wave mixing
- Photon echoes
- Three-wave mixing
- Electrostrictive effects in aerosols
- Photorefractive effects in semiconductors
- Plasma production.

Applications of optical phase conjugation include image enhancement, distortion correction, pointing and tracking, improved laser resonators, and lensless imaging.

II. THEORY

A. PHASE CONJUGATION--A PHYSICAL INTERPRETATION

Optical phase conjugation reverses the direction of propagation and the overall phase factor of a beam of light. The process resembles that of reflection from an ordinary mirror with two fundamental differences. As illustrated in Figure 1a, an ordinary mirror exhibits the familiar beam redirection associated with the sign change of the normal component of the k-vector while leaving the transverse components unchanged. In a phase conjugate mirror (Figure 1b), the transverse components as well as the normal

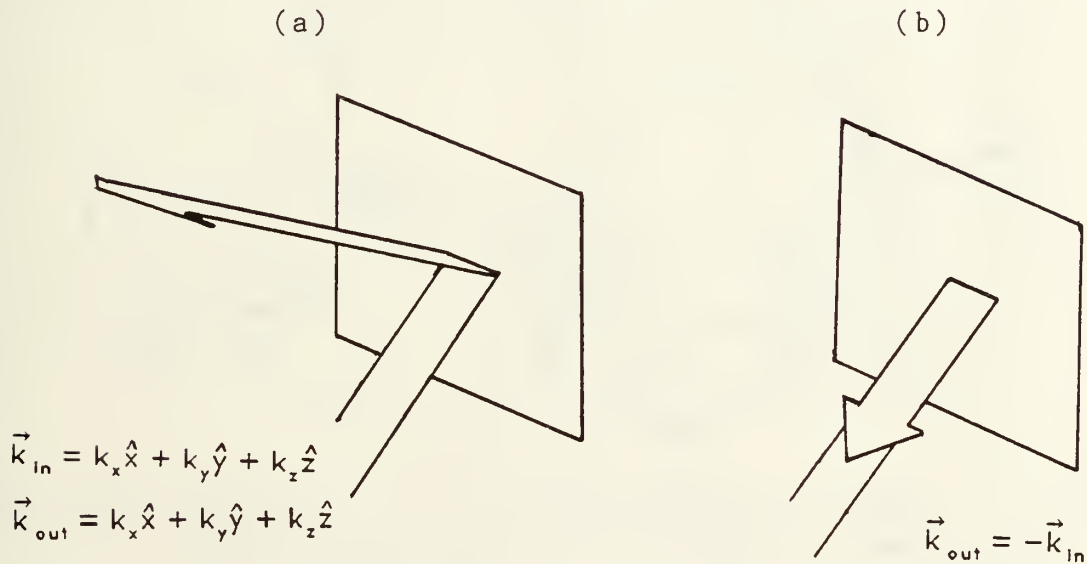


Figure 1. (a) Ordinary Mirror (b) Phase Conjugate Mirror
[Ref. 1: p. 3]

component of the k -vector have a sign change. This "perfect" reversal of the beam redirects the outgoing beam exactly back along its original path. Note that with a conventional mirror we may arbitrarily steer a beam by changing the tilt of the mirror. With a phase conjugate mirror tilting the mirror has no effect on the direction of the "reflected" beam. The beam will always retrace its original path. This is the first fundamental difference between a conventional and a phase conjugate mirror.

If we were to redirect the beam by means of a prism (Figure 2), the phase conjugate mirror would reflect the beam to the same spot on the prism. After traversing the prism the beam would return via the original path to its source.

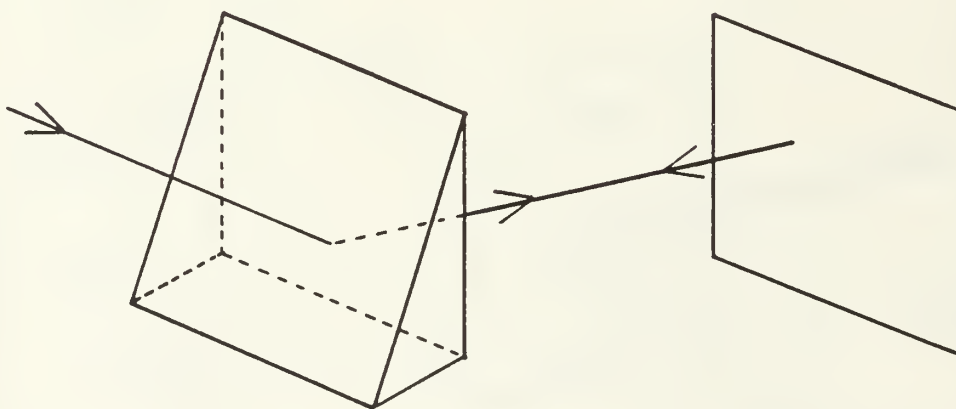


Figure 2. Effect of Distortion on Phase Conjugate Reflection
[Ref. 1: p. 4]

Since we may extrapolate this argument to an infinite number of random distortions we have demonstrated one of the

fascinating properties of optical phase conjugation--phase distortion correction.

The second property which distinguishes the phase conjugate mirror from an ordinary mirror is that the mirror forms the complex conjugate of the electric field. Not only does the conjugate beam return along the same path as the original beam, but the wavefront of the conjugate beam exactly matches at every point in space the wavefront of the original beam. This concept is illustrated in Figure 3.

The net effect of the conjugation process is the production of a beam of light that behaves like the time reversed image of the original beam. If we had filmed a wavefront of the beam along its path from the source to the mirror, the reflected phase conjugate wavefront would appear identical to the image on the film run backwards.



Figure 3. Distortion "Undoing" Property of Phase Conjugation

B. THE UNDOING THEOREM

To prove the distortion restoring properties of the phase conjugate wave, we consider the right going wave of Figure 3 to be the form

$$E_1(\vec{r}, t) = \Psi_1(\vec{r}) \exp[i(\omega t - kz)] . \quad (1)$$

The wave equation is

$$\nabla^2 \Psi_1 + [\omega^2 \mu \varepsilon(\vec{r}) - k^2] \Psi_1 - 2ik \frac{\partial \Psi_1}{\partial z} = 0 , \quad (2)$$

and the complex conjugate is

$$\nabla^2 \Psi_1^* + [\omega^2 \mu \varepsilon(\vec{r})^* - k^2] \Psi_1^* + 2ik \frac{\partial \Psi_1^*}{\partial z} = 0 . \quad (3)$$

If the left going wave is of the form

$$E_2(\vec{r}, t) = \Psi_2(\vec{r}) \exp[i(\omega t + kz)] , \quad (4)$$

then the wave equation becomes

$$\nabla^2 \Psi_2 + [\omega^2 \mu \varepsilon(\vec{r}) - k^2] \Psi_2 + 2ik \frac{\partial \Psi_2}{\partial z} = 0 . \quad (5)$$

Provided $\varepsilon(\vec{r}) = \varepsilon(\vec{r})^*$, which means a real and thus lossless (and gainless) medium, equations (3) and (5) are the same since $\Psi_1(\vec{r})^*$, and $\Psi_2(\vec{r})$ satisfy the same differential equation. Thus if $\Psi_2(\vec{r}) = a \Psi_1(\vec{r})^*$, (where a is an arbitrary constant) over any plane in space ($z = 0$ for example) then due to the uniqueness theorem, $\Psi_2(\vec{r}) = a \Psi_1(\vec{r})^*$, at all points ($z < 0$). [Ref. 2: pp. 500-501]

We have shown by the above proof that after a beam traverses a distorting medium (where $\epsilon(\vec{r})$ is real) a phase conjugate beam can travel backwards through the medium and at all times its wavefronts will coincide with the wavefronts of the original beam. We now proceed to derive the nonlinear wave equation.

C. THE WAVE EQUATION

Maxwell's Equations in SI units are:

$$\begin{aligned}\vec{\nabla} \cdot \vec{D} &= \rho \\ \vec{\nabla} \cdot \vec{B} &= 0 \\ \vec{\nabla} \times \vec{H} &= \vec{J} + \frac{\partial \vec{D}}{\partial t} \\ \vec{\nabla} \times \vec{E} &= - \frac{\partial \vec{B}}{\partial t}.\end{aligned}\tag{6}$$

We assume the medium to be homogeneous, nonmagnetic, and nonconducting, and that there are no free charges. Writing the displacement vector, $\vec{D}$, in terms of the electric field and the polarization we have

$$\vec{D} = \epsilon_0 \vec{E} + \vec{P},\tag{7}$$

where

$$\vec{P} = \vec{P}_L + \vec{P}_{NL}\tag{8}$$

has been broken into linear and nonlinear components. We then derive the wave equation, assuming transverse waves, by taking the curl of the last of Maxwell's Equations above and making use of the operator identity $\vec{\nabla} \times (\vec{\nabla} \times \vec{F}) = \vec{\nabla}(\vec{\nabla} \cdot \vec{F}) - \nabla^2 \vec{F}$. The resulting plane wave equation is

$$\nabla^2 \vec{E} - \mu_0 \epsilon \frac{\partial^2 \vec{E}}{\partial t^2} = \mu_0 \frac{\partial^2 P_{NL}}{\partial t^2}. \quad (9)$$

Note that if the polarization were linear, the righthand side would be zero, the familiar linear wave equation. The above equation shows how an electric field may be produced in the presence of a nonlinear polarization. In a linear medium many electromagnetic waves may exist simultaneously, but they are independent and do not couple. In a nonlinear medium, coupling may occur and produce new waves. The existence of a nonlinear polarization is therefore a necessary condition for the generation of a (new) conjugate wave.

The polarization is related to the electric field by the equation

$$\vec{P}(E) = \chi(E) \vec{E}, \quad (10)$$

where χ is the field dependent electric susceptibility of the medium. In this case, E is the total field which may be comprised of many different waves at different frequencies. If we expand the susceptibility in a power series, we have

$$\chi(E) = \chi^{(1)} + \chi^{(2)} E + \chi^{(3)} E^2 + \dots, \quad (11)$$

and the polarization becomes

$$P(E) = \chi^{(1)}E + \chi^{(2)}E^2 + \chi^{(3)}E^3 + \dots \quad (12)$$

The first term in the above equation is linear in E and by equation (9) cannot not be responsible for the generation of a phase conjugate wave. The higher order terms are capable of coupling waves and under certain conditions will produce a phase conjugate wave.

D. GENERATION OF A PHASE CONJUGATE WAVE BY STIMULATED BRILLOUIN SCATTERING

Although many nonlinear effects give rise to a phase conjugate wave, the process of stimulated Brillouin scattering (SBS) has several advantages over other methods. Namely,

- SBS requires no auxiliary (pump) beams
- Nonconjugate waves have substantially lower gain than the conjugate wave
- The frequency shift between the input beam and phase conjugate beam is very small, allowing a pulse to be amplified, conjugated, and then amplified again on its return passage through the amplifier
- Very little energy is left behind in the SBS medium.

1. What is SBS?

Stimulated Brillouin scattering is a third-order effect of the susceptibility of the medium and closely resembles another third-order effect, stimulated Raman scattering. In fact, there are many similarities among the various photon scattering processes (Rayleigh, Raman,

Brillouin, fluorescence, etc.) and not by coincidence they each may be explained in terms similar to Einstein's spontaneous and stimulated emission energy level diagrams. In Raman scattering, for example, a light wave scatters via interaction with molecular vibrations and rotations or longitudinal phonons of a crystal lattice. As illustrated in Figure 4, a photon of frequency ν_i (from a laser source for instance) and another photon of frequency ν_s (corresponding to some characteristic frequency) are simultaneously incident on a molecule. The molecule gains energy $h\nu_i$ and subsequently is stimulated by the other photon to emit an additional photon of energy $h\nu_s$. In this manner scattered photons may be generated at the expense of the pump photons. Above a certain threshold of incident photon flux, the scattered photons have gain.

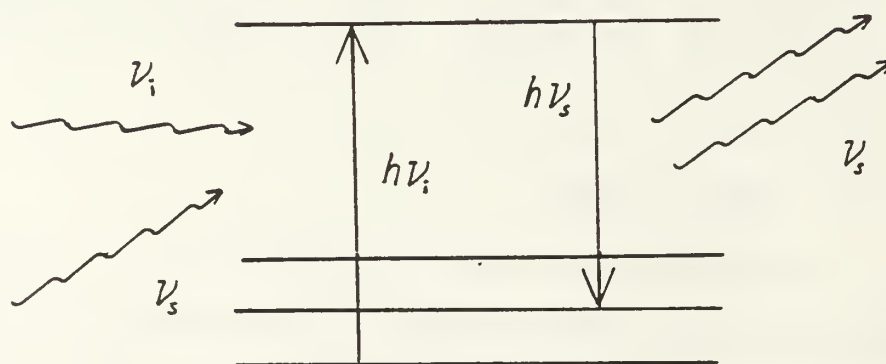


Figure 4. Stimulated Raman Scattering

In SBS, the coupling of the incident and scattered wave occurs by means of scattering from an acoustic wave. If we have a liquid medium consisting of molecules that are easily polarized (carbon disulfide for example) a strong electric field applied to the liquid will create a compression wave through the process of electrostriction. This wave propagates through the medium at the characteristic acoustic velocity, v_s . The incoming wave of frequency ν_i Bragg scatters off this periodic acoustic wave producing a new scattered wave of frequency ν_d . The process is shown schematically in Figure 5. The entire process may be thought of as a Doppler shift off a moving grating of velocity v_s . [Ref. 3 and Ref. 4]

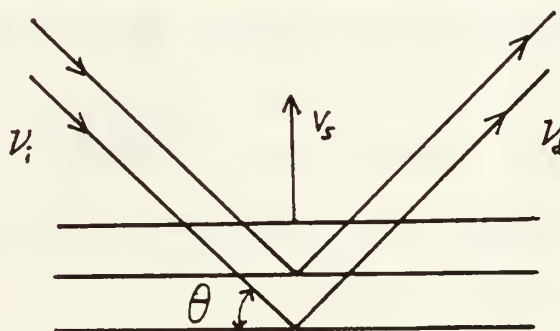


Figure 5. Stimulated Brillouin Scattering

We may solve the geometry problem illustrated by Figure 5 for the frequency of the backscattered wave. The

Bragg law is in general given by

$$m \frac{\lambda}{n} = 2d \sin \theta , \quad (13)$$

where m is an integer, n the index of refraction, and d is a spacing of reflectors (diffractors). This equation is generally seen in the context of scattering from a crystal lattice but is appropriate for scattering via sound waves with slight modification. In the case of scattering from a crystal, the reflectors are discrete planes hence the integer index, m . In a reflection from an acoustic wave we have a continuous medium whose periodic nature arises from a smoothly varying property (index of refraction). In this case, the solution provides for constructive interference of wavefronts only for $m = 1$ [Ref. 5]. Additionally the periodic spacing, d , corresponds to the wavelength, λ_s , of the acoustic wave. Hence equation (13) becomes

$$\frac{\lambda}{n} = 2\lambda_s \sin \theta . \quad (14)$$

We may apply the formula for a Doppler frequency shift to the geometry of Figure 5

$$\Delta \nu = 2\nu \frac{v}{c/n} , \quad (15)$$

where v is the velocity component parallel to the propagation vector of the incident wave. Thus equation (15) becomes

$$\Delta \nu = 2\nu \frac{v_s \sin \theta}{c/n} . \quad (16)$$

Substituting equation (14) for $\sin\theta$

$$\Delta\nu = \frac{v_s}{\lambda_s} = \nu_s . \quad (17)$$

We see that the frequency shift is equal to the frequency of the acoustic vibration. If we had approached this from a consideration of conservation of energy we would have

$$E_{\text{incident}} = E_{\text{diffracted}} + E_{\text{acoustic}}$$

$$h\nu_i = h\nu_d + h\nu_s , \quad (18)$$

$$\Delta\nu \equiv \nu_i - \nu_d = \nu_s ,$$

where we have quantized the acoustic energy (phonons) as well as that of the light beams.

We must also satisfy the law of conservation of momentum which is illustrated by Figure 6. For a transverse wave incident on a liquid medium such as CS_2 , the acoustic wave generated will be primarily longitudinal (i.e. $\vec{k}_i$ and $\vec{q}$ are mostly colinear). This means that the backscattered

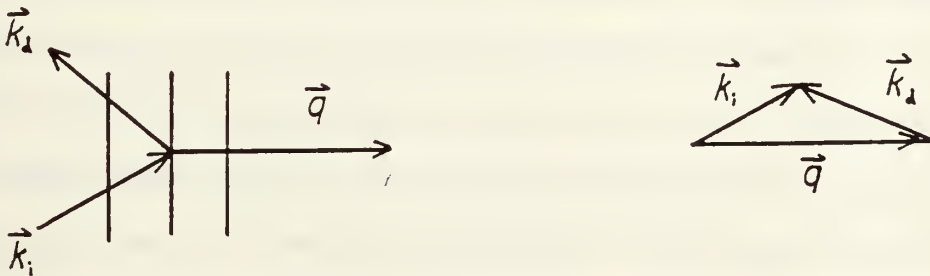


Figure 6. Relation of Wave Vectors in SBS

k-vector will be opposite that of the incoming k-vector. This is precisely one of the conditions we require for phase conjugation.

Another condition which must be satisfied in order for the backscattered wave to behave as the time reversed image of the incoming wave is that the frequency shift be small. If not, the beam will deviate from the original path as it traverses regions of frequency dependent dielectric properties. Returning to equation (16) we have a fractional frequency shift given by

$$\frac{\Delta \nu}{\nu} = \frac{2v_s n}{c} \sin \theta \quad (19)$$

which is maximized for scattering in the backward direction. This frequency shift is not desired, however for acoustic velocities (~ 1000 m/s) the shift will be small ($\sim 10^{-5}$).

2. The Phase Conjugate Solution

The process of SBS is initiated by spontaneously scattered light (noise) just as in a laser and the processes of Bragg scattering and electrostriction will reinforce each other above a certain threshold (i.e. there will be gain). Zel'dovich et al. first reported [Ref. 6] that SBS in the backward direction would be phase conjugate. Solutions to Maxwell's Equations for the newly generated backscattered wave worked out by Sidorovich [Ref. 7] and expanded upon by Hellwarth [Ref. 8] provide for one mode of oscillation which is nearly phase conjugate and has an exponential gain factor

nearly twice that of the next largest mode. Thus, under proper conditions, a backscattered wave that is phase conjugate will be generated, and it will be the dominant (backscattered) wave.

In order to phase conjugate a significant portion of an incident beam, we require enough stimulated gain ($\sim 10^{12}$) so that the spontaneously scattered light is sufficiently amplified in a single pass through the interaction length. Hellwarth [Ref. 8] works out the details of this interaction for the case of a beam in a waveguide and makes several conclusions concerning the case of an unguided beam, for which earlier experiments were conducted by Zel'dovich, et al. (1972).

In general, an unguided beam will require more power and is subject to undesired effects such as self-focusing, breakdown, etc. Some researchers have concluded that a waveguide may in fact be necessary for satisfactory distortion correction [Ref. 9]. Nonetheless, the restrictions on phase conjugation appear sufficiently broad, based upon preliminary theoretical studies, so that phase conjugation can be achieved satisfactorily without imposing the requirement for a guide.

Hellwarth states that earlier work [Ref. 7] was much too restrictive on the requirements for phase conjugation. Specifically he concludes that

- Large differences in amplitudes of excited modes are not detrimental to phase conjugation
- The waveguide does not have to be much longer than a diffraction length
- The incident beam solid angle does not have to be greater than the change in the nonlinear index of refraction.

Other requirements which must be considered are the interaction length which is derived for the case of stimulated Raman scattering (SRS) in a waveguide but which we will take as an order of magnitude approximation. From [Ref. 8],

$$L \leq 6\sqrt{r_0} S/N\Delta\lambda \quad , \quad (20)$$

where L is the interaction length, r_0 is the maximum allowed fraction of the backscattered beam that is not phase conjugate, S is the area of the guide, $\Delta\lambda$ is the wavelength shift in the medium, and N is the number of excited transverse mode patterns of the guide.

Finally, Hellwarth concludes that for scattering without a waveguide the interaction may be taken to occur in a length one diffraction length long. Or

$$L_{\text{DIFFRACTION}} \sim S/\lambda\sqrt{N} \quad (21)$$

where S is the area of an equivalent waveguide whose cross-section would just encompass the least number of free space Gaussian beam modes, N , needed to give a good representation of the focused beam. [Ref. 8: p. 1056]

III. EXPERIMENTAL DESIGN

A. THEORETICAL CONSIDERATIONS AND LIMITATIONS

The ease with which a particular physical process may be induced has a direct bearing on its potential for use in any practical device. With this in mind, we conducted the experiment with no highly specialized equipment, using only those facilities immediately available at the Naval Postgraduate School.

The first laser which we attempted to phase conjugate was a one watt Argon-ion laser. After this proved unsuccessful, it was determined that there was insufficient power available to produce detectable backscatter. A pulsed laser was needed to increase the peak E field. A computation of the power output of an available Nd-glass oscillator-amplifier laser yielded a pulse power on the order of 40MW for the oscillator alone. The laser had a beam diameter of ~ 2 cm, and a corresponding power density of approximately 10 MW/cm^2 . Hellwarth [Ref. 10] derives the reflectivity of a "Brillouin mirror" for the case of a medium pumped by two counter propagating beams of intensity I_G and I_H .

$$R = I_G I_H \beta^2 L^2, \quad (22)$$

where L is the interaction length and β is a frequency dependent coupling factor.

$$\beta = \frac{|96\pi^2 \omega c_{ijk} f_i^* e_j^* g_k h_l|}{c} . \quad (23)$$

Since we are relying on the self-pumping aspect of SBS we will postulate that the input beam acts as one pump beam (I_G) and that stimulated backscattered waves act as the other pump beam (I_H). If we assume that I_H is some small fraction of I_G , say 1% then equation (22) becomes

$$I_G = \frac{10}{\beta L} \sqrt{R} . \quad (24)$$

Of course if we have gain in the interaction region (our desired result), $I_H \sim I_G$. But we will ignore this contradiction as we endeavor to see if we have sufficient power to "bootstrap" our experiment into operation.

For CS_2 and $\lambda \sim 10^{-6} \mu m$, $\beta \sim 10^{-3} \text{ cm /MW}$. If we desire $R \sim 1$ in an interaction length of approximately 10 cm, we require $I \sim 1 \text{ GW/cm}^2$. Since we cannot realize this density even with the amplifier, we must focus the beam. A lens of focal length 10 cm will yield a diffraction limited beam size of

$$r = \frac{\lambda f}{\pi D} , \quad (25)$$

where r is the beam diameter at the focal spot, f is the focal length, and D is the lens diameter. Since the calculation of r yields $\sim 10^{-4} \text{ cm}$, we will achieve the necessary order of magnitude power density somewhere within the focal cone of the lens.

We now consider the restriction on interaction length given by equation (20). We will assume that if 50% of the backscatter is a phase conjugate component, we will be able to detect its presence. Additionally we will take S to be equal to the area of the focal spot ($\sim 10^{-12} \text{ m}^2$) although the area of the beam cross-section in the interaction region is probably slightly larger, and we have the wavelength shift [computed from the frequency shift of equation (19)] to be $\sim 10^{-11} \text{ m}$. For a value of N we will assume that every transverse mode of the Nd-glass laser which has gain (~ 1000) excites one transverse mode in the medium. With these values we find that the interaction length must be less than $150 \mu\text{m}$ (~ 150 wavelengths). From our earlier calculation of required energy density we expect the interaction to take place over a short path length.

From equation (21) we approximate the interaction to be $\sim 10^{-2} \mu\text{m}$, which is less than the value computed by equation (20) by several orders of magnitude. The entire interaction occurs (if it occurs) essentially in a plane, hence the mirror analogy used earlier is quite appropriate. We may conclude from these calculations that there is a possibility of achieving phase conjugation with the system we propose to use.

We must not, of course, become too optimistic by the above calculations for there is at least one unknown which we have not addressed. The majority of phase conjugate theories

have been derived for a monochromatic, single mode (TEM_{00}) beam. It is known however that the laser we have used for this experiment has a broad linewidth. Additionally, attempts at tuning it to something resembling a TEM_{00} mode have not been successful.

B. PHYSICAL LAYOUT

The layout of the experiment is illustrated in Figure 7. The laser used was a Q switched Nd-glass laser ($\lambda = 1.059 \mu m$) consisting of an oscillator and amplifier. The oscillator alone was capable of producing approximately a one joule, 25 nanosecond pulse. With the oscillator-amplifier combination a five to seven joule pulse was easily achieved. The beam diameter out of the amplifier was approximately 2 cm. Phase distortion was introduced by means of a chemically (HF acid) etched glass plate (P1) which could also be used to reflect part of the beam to an energy meter. Beam sampling was accomplished by means of glass plates (P2 and P3) oriented to capture the input beam and the return (conjugate) beam, if any.

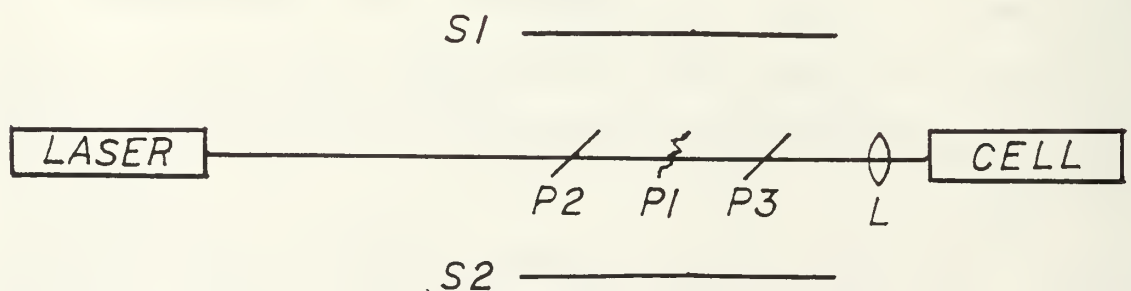


Figure 7. Layout of the Experiment

A 10 cm lens (L) focused the beam into a cell (C) containing carbon disulfide (CS_2).

The image of the beam reflected from P2 or P3 was projected on screens S1 and S2 where it could be viewed by means of a handheld IR viewer. Additionally, burn patterns could be produced on suitable materials located at S1 and S2. Ordinary carbon paper produced the best results for these burn patterns, although photographic reproduction of the carbon paper produced poor results. For more quantitative information, the energy meter was oriented to capture the input or return beam from P2.

The lens (L) and the cell (C) were tilted with respect to the laser axis approximately 15 degrees to minimize specular reflection from those surfaces.

C. TEST PROCEDURE

Due to the inability to control the laser output power even over a moderate range and the availability of only one energy meter, all data obtained were viewed as a statistical data base and analyzed accordingly.

The first test shots were made with the oscillator alone (the amplifier being physically removed) and early results were negative. After careful alignment of the laser and experimenting with various pumping levels (power supply voltages of 3.75 KV to 5.0 KV) a significant backscattered

wave appeared visually (with the IR viewer) and produced burn patterns.

Four types of quantitative measurements were made

- Input beam energy
- Backscattered beam energy when phase conjugation was observed either visually or by burn patterns
- Backscattered beam energy when no phase conjugation was observed
- Energy associated with ordinary (specular) reflection from the lens and an empty cell.

Qualitative observations were made of

- The nature of the interaction within the liquid
- Effects of breakdown on the quality of the backscattered beam
- Ability of the backscattered beam to correct distortions introduced on the input beam.

Ideally, two energy meters are needed to measure the initial beam energy and the backscattered energy. Only one energy meter was available so a statistical approach was used. During an experiment a series of shots (~ 5) were made and the energy of the input beam recorded by an energy meter located to receive the return from P2. The meter position was then moved to a position along S2 and another series of shots were made while noting whether the return beam generated a spot size of the order of the input beam. If a spot was observed this was interpreted as being generated by SBS within the cell. The meter was then returned to the original position for another series of shots. This

technique was used in order to average out fluctuations of the laser output.

Next, CS_2 was removed from the cell and the above procedure repeated to determine the level of normally reflected energy. All of these initial measurements were conducted without the distortion plate in place.

After the fraction of backscattered energy was determined, the effect of phase distortions were studied. The phase plate (P1) was placed in the beam path and positioned to reflect a portion of the beam to the energy meter in order to monitor the energy output of the laser. Carbon paper was placed at S1 and S2 to produce burn patterns of the input, distorted, and return beam.

During all portions of the experiment, the nature of the interaction within the cell was observed visually and several photographs were produced.

IV. RESULTS

The first conclusive result was that the laser pulse produced a very large acoustic wave within the liquid. The fill tube stopper on the cell was repeatedly dislodged from the cell by the fluid pressure within.

Not to be dissuaded, the stopper was secured more firmly and remained in place on the subsequent shots. However, the rear window of the cell subsequently shattered. The rear window was replaced, but failed again after a limited number of shots. A new cell was fabricated from a pyrex window bonded with RTV to a chemistry flask of much heavier glass and this proved to be an adequate vessel.

Eventually, a significant backscattered wave occurred. To determine if this was indeed a phase conjugate wave, the lens, cell, and other possible reflecting surfaces were rotated. This had no effect on the position of the return beam, strong evidence that phase conjugation had been achieved.

A. DEPENDENCE ON LASER

Actually achieving a significant backscattered wave was a difficult and tedious process and this difficulty was attributed to the broad linewidth and multimode nature of the laser.

Two particular techniques appeared to improve the probability of generating a backscattered wave:

- Pumping the system as hard as possible (5.00 KV)
- Pumping the system just hard enough so that lasing occurred (3.75 KV).

The improvement realized by the first technique is attributed to achieving fewer modes of oscillation by forced dumping of energy into preferred modes. The second improvement should come from decreasing the number of longitudinal modes that have gain. Although this is just speculation, the fact remains that a backscattered wave was seldom observed when pump levels other than the minimum (3.75 KV) or maximum (5.0 KV) were used. Backscatter using a Nd-YAG in CS₂ pervades the literature. Since a Nd-YAG laser has a linewidth almost two orders of magnitude less than a Nd-glass laser this suggests that laser linewidth and number of modes present are significant contributing factors to phase conjugation.

B. BACKSCATTERED ENERGY

Appendix A contains numerical data from the series of experiments using the Nd-glass laser focused into the fabricated cell. The backscattered beam contained approximately 33% of the incident beam energy. Of this approximately 2.5% was attributed to normal reflection from the various glass surfaces (obtained by firing the laser into an empty cell). These values were obtained by the methods described in Section IIIC after subtracting an appropriate

noise estimate. Noise components were determined by completely obstructing the main beam and recording meter response for a series of shots. Apparently, EMI and acoustic noise produced measurable readings in the energy meter.

No significant difference in the amount of scatter from the empty cell and from the cell filled with CS_2 occurred when phase conjugation was inhibited (by defocusing) or when for some unknown reason phase conjugation was not observed.

There was no significant difference noted in energy returned when breakdown occurred in the CS_2 and when there was no breakdown. However breakdown almost always occurred and the effect of this on the backscattered beam is inconclusive.

C. DISTORTION CORRECTION

The profile of the beam introduced by a spatial filter was altered significantly by the phase distortion plate and the conjugate beam showed complete restoration (Figure 7). It was noted, however, that a reduction in reflected power (a 67% reduction in this case) could give the appearance of "healing" of beam distortions due to the low sensitivity of the exposed recording media (carbon paper). But the degree of restoration was too complete to be accounted for by energy loss alone. A comparison of a beam reflected from an ordinary mirror with a 62% neutral density transmission filter interposed (38% transmission round trip) confirmed

(a)



(b)

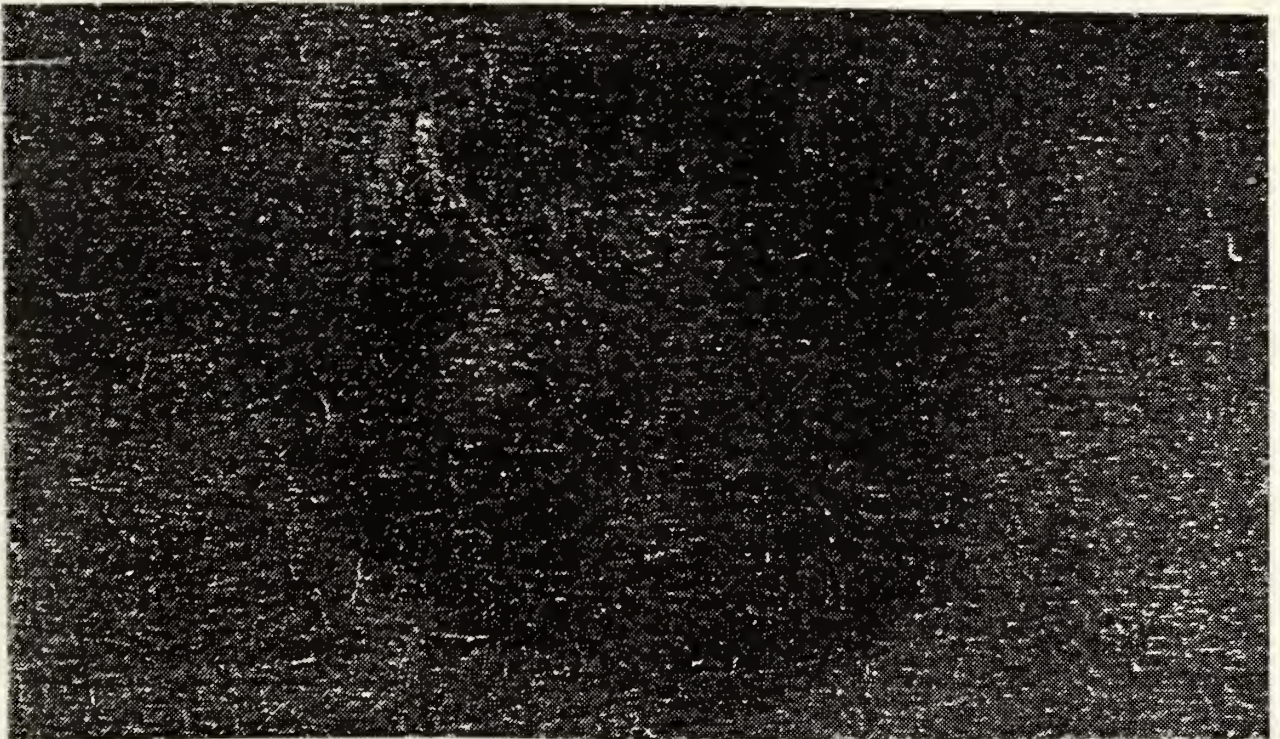


Figure 7. (a) Burn Pattern on Carbon Paper of Input Beam (left) and Distorted Beam (right). (b) Return Phase Conjugate Beam (enlarged).

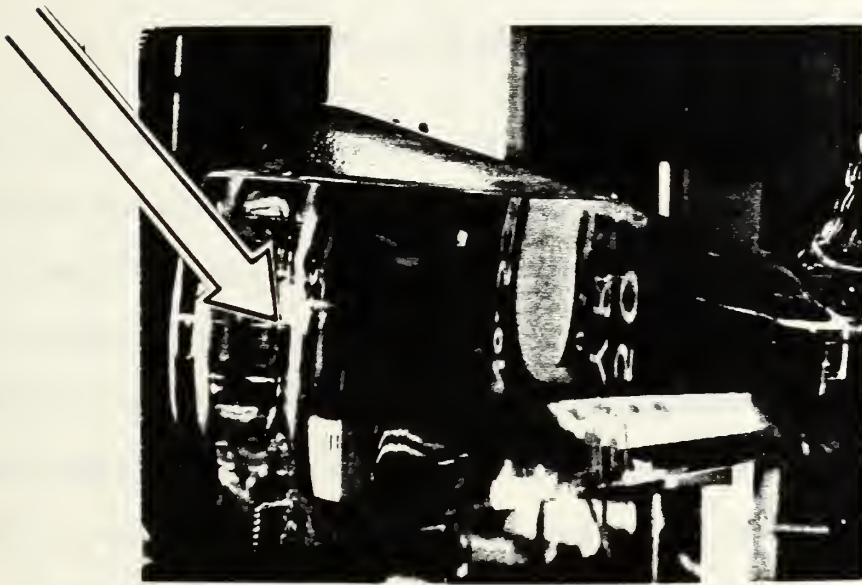
this. Spatial patterns of fine structure imposed on the beam showed slight improvement in distortion correction, however the attenuation of the input beam seemed to adversely effect the performance of the phase conjugation process.

Additionally, the small phase distortion introduced by the distortion plate coupled with the relatively short propagation distance hampered the determination of distortion correction.

D. FLUORESCENCE

A general observation of the interaction of the focused beam with liquid in the cell was made and perhaps warrants further study. Specifically it was noted that when phase conjugation occurred there was a significant amount of fluorescence (in the visible spectrum) observed within the focal cone in the liquid. This effect seemed to be independent of the energy of the pulse. If phase conjugation did not occur, the fluorescence was not observed. In both cases, arcing in the vicinity of the focal spot was generally observed. (Figure 8)

(a)



(b)



Figure 8. (a) No Phase Conjugate Return was Observed during this Pulse. (b) Phase Conjugate Return was Observed from this Pulse. Note Large Fluorescence within Focal Cone.

V. RECOMMENDATIONS

A purpose of this experiment was to determine if phase conjugation could be achieved simply with available optical equipment. As such, the results presented in Section IV should be considered as a general indication of what a researcher might expect from a refined experiment in phase conjugation. More detailed and precise measurements would be desired, particularly in the laser beam profile and pulse energy areas. Some of these measurements might not be possible with the particular system used in this research. Specifically, the following investigations would be of value:

- Dependence on monochromaticity using a spectrum analyzer and (slightly) detuned laser
- Mode dependence of phase conjugation
- Energy threshold of phase conjugation
- Quantitative measurements of distortion correction possibly using a beam profiler
- Comparison of phase conjugation in a waveguide with that in an infinite (guideless) medium
- Phase conjugation in other media and/or via other physical processes.

VI. CONCLUSION

In summary, we have shown that optical phase conjugation is a relatively easily achieved process. Although the presence of a complicated mode structure seems to interfere with the phase conjugation process we observed a backscattered return amounting to 33% of the incident beam. This amount of return cannot be accounted for by normal reflection from the glass surfaces. Additionally, the backscattered return exhibits several of the properties that define a phase conjugate wave--path reversal and distortion correction. Whether phase conjugation occurred depended to a large extent on how the laser was pumped. Those pumping techniques that favor the generation of a few strong modes produced better results than those which produce many modes of various intensities. Finally, the observance of significant fluorescence in the vicinity of the interaction region has not been satisfactorily explained and warrants further investigation.

APPENDIX A
TABLE OF EXPERIMENTAL DATA

Shot #	Input beam energy (joules)
1	6.25
2	5.44
3	5.67
4	6.82
5	6.92
6	----
7	7.64
8	6.51
9	7.15
10	6.51
11	6.94
12	6.57
Average	6.58 $\pm$.23

Shot #	Backscattered beam energy (joules)
1	3.06
2	2.75
3	2.16
4	2.67
5	----
6	2.88
7	2.72
8	2.68
9	2.72
10	2.50
11	3.16
12	----
Average	2.73 $\pm$.16

APPENDIX A

TABLE OF EXPERIMENTAL DATA

Shot #	Reflected energy from glass surfaces (empty cell) (joules)
1	1.04
2	0.99
3	0.96
4	1.03
5	1.02
6	1.02
7	0.98
8	0.97
9	1.01
10	1.00
11	0.99
12	0.93
Average	1.00 $\pm$.05

Shot #	Noise (meter reading with beam obstructed) (joules)
1	0.95
2	0.80
3	0.92
4	0.76
5	0.96
6	0.77
7	0.70
8	0.97
9	0.83
10	0.92
11	0.79
12	0.78
Average	0.85 $\pm$.09

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